

# 41<sup>st</sup> Joint Propulsion Conference and Exhibit

Tuscon, Arizona

July 13-14, 2005

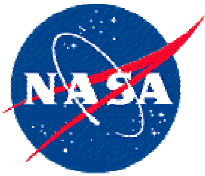
**Sub-Topic:  
Liquid Rocket Engine Testing**

***AIAA Short Course on  
Liquid Rocket Engines***

Dr. Shamim Rahman

NASA John C. Stennis Space Center, MS





# Section Outline

*AIAA LRE Course*

- Objectives and Motivation for Testing
  - Technology, RDT&E, Evolutionary
- Representative LRE Test Campaigns
  - Apollo, Shuttle, ELV Propulsion
- Overview of Test Facilities for Liquid Rocket Engines
  - Boost, Upper Stage (Sea-level and Altitude)
- Statistics (historical) of Liquid Rocket Engine Testing
  - LOX/LH, LOX/RP, Other development
- Test Project Enablers: Engineering Tools, Operations, Processes, Infrastructure

*Continued on Next Page ...*



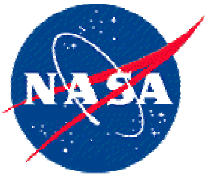
## Section Outline (cont.)

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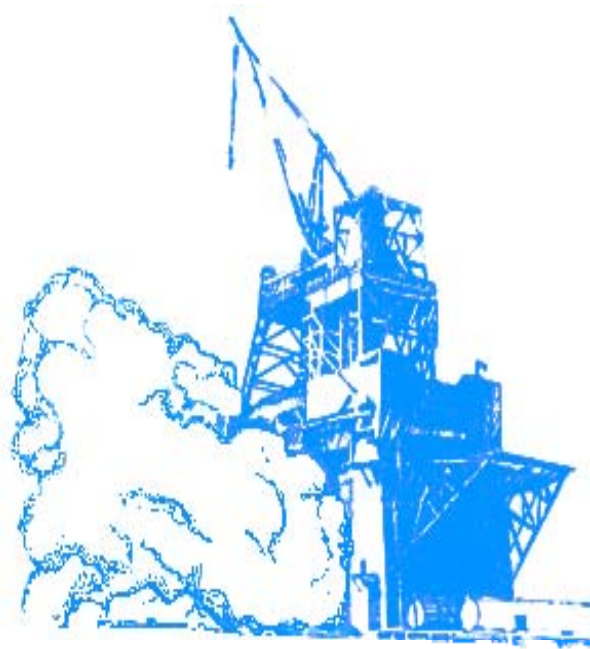
*AIAA LRE Course*

*Continued from Previous Page ...*

- Non-NASA Test Capability (CPIA)
  - National Rocket Propulsion Test Alliance
  - Commercial Test Sites
  - University Test Sites
- Summary
- BACKUP MATERIAL



# ***OBJECTIVES & MOTIVATION FOR LRE TESTING***





# Key Terms

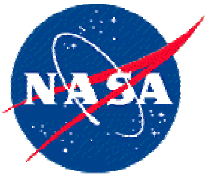
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- **Development** testing is required to achieve design maturity, demonstrate capability, and to reduce risk to the qualification program. Development tests are conducted, as required, to:
  - Validate new design concepts or the application of proven concepts and techniques to a new configuration,
  - Assist in the evolution of designs from the conceptual phase to the operational phase,
  - Validate design changes,
  - Reduce the risk involved in committing designs to the fabrication of qualification and flight hardware,
  - Develop and validate qualification and acceptance test procedures,
  - Investigate problems or concerns that arise after successful qualification,

An objective of development testing is to identify problems early in their design evolution so that any required corrective actions can be taken prior to starting formal qualification testing.
- **Qualification** tests (also commonly known as **certification** tests) are conducted to:
  - Demonstrate that the design, manufacturing process, and acceptance program produce hardware/software that meet specification requirements with adequate margin to accommodate multiple rework and test cycles,
  - In addition, the qualification tests should validate the planned acceptance program, including test techniques, procedures, equipment, instrumentation, and software.

Generally qualification follows completion of the development test program.
- **Acceptance** tests are conducted to demonstrate the acceptability of each deliverable item to meet performance specification and demonstrate error-free workmanship in manufacturing. Acceptance testing is intended to:
  - Stress screen items to precipitate incipient failures due to latent defects in parts, processes, materials, and workmanship,
  - Component acceptance testing at the bench level serves to reduce risk for engine acceptance testing, but it may not simulate the engine environments adequately.

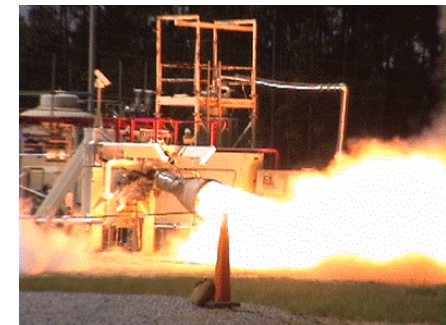
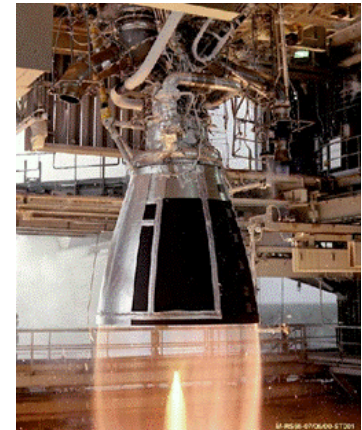
Many components require engine hot fire to adequately reduce flight risk. (An engine LRU is a component that may be removed and replaced by a new unit, without requiring reacceptance test firing of the engine with the new unit. If the unit being replaced was included in an engine acceptance test firing as part of its acceptance test, then the replacement unit either should be subjected to such a test on an engine, or should undergo equivalent unit-level acceptance testing).



# Objectives of Liquid Propulsion Testing

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- Component Development
  - Combustion devices (turbomachinery, chambers, ignitors), e.g. RS-84
  - Advanced technology demonstrators
- Prototype Engine Development
  - J-2 S, XRS-2200, RL-60, MB-60
- Flight Engine Qualification, Certification
  - J-2, F-1, SSME, RS-68, RL-10, etc.
- Flight Engine Acceptance
  - RS-68, SSME
- Major Engine Upgrades
  - SSME Block Upgrades
- Re-development and Re-Use Potential
  - LR-89 thrust chamber

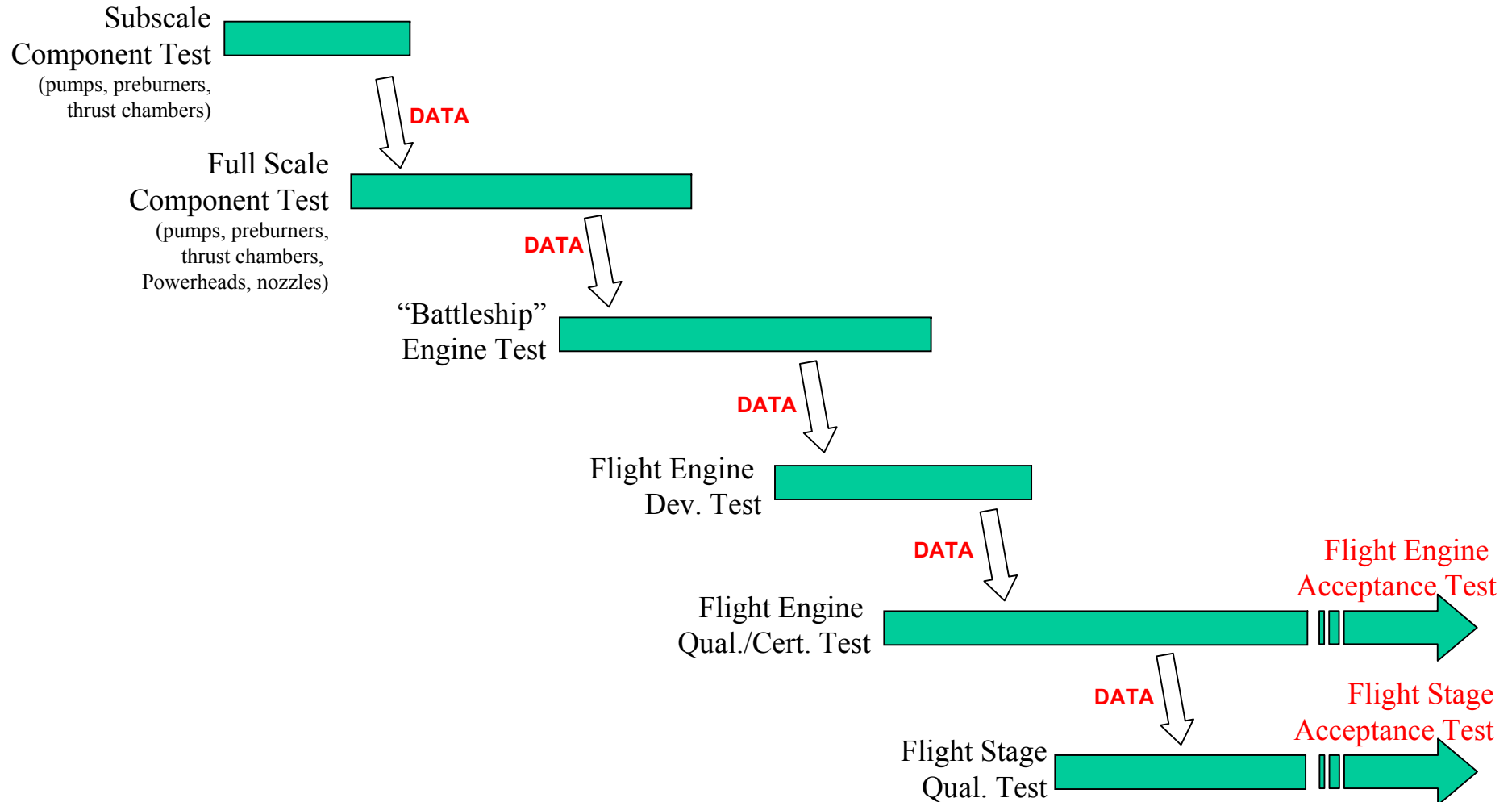


*Some examples of each are listed*



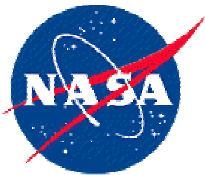
# Typical Sequence of Testing

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- An On-going process of risk reduction (components, engines, stages)



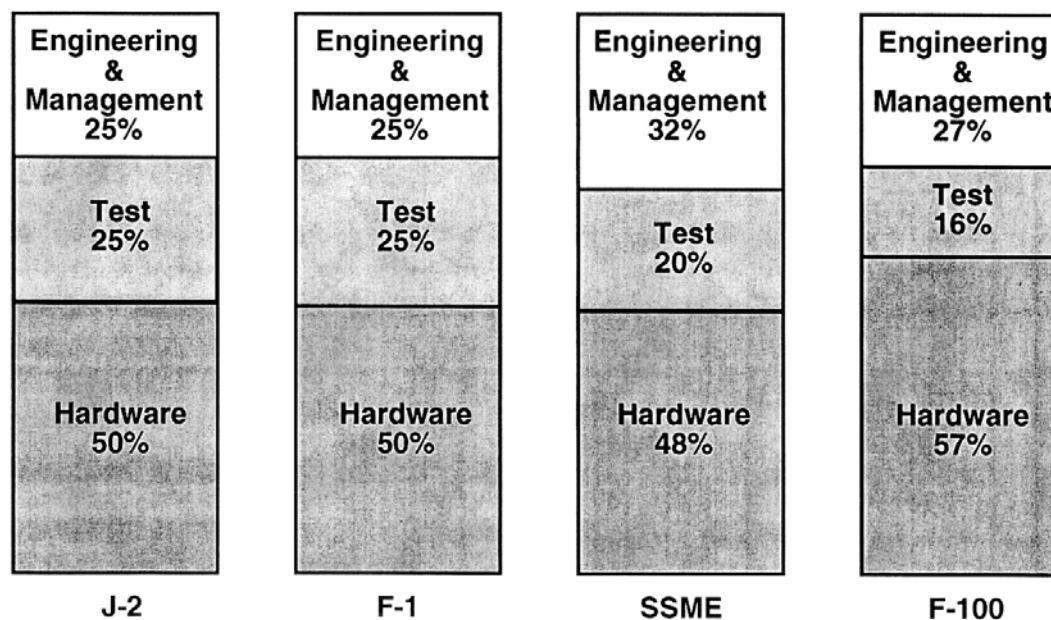


# Testing Cost / Total Cost for Propulsion

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## Historical Full Scale Development Cost Distribution

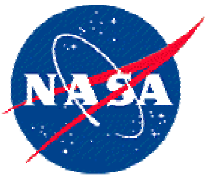
History shows major cost elements are consistent



REDT-DF6/93-02/29-

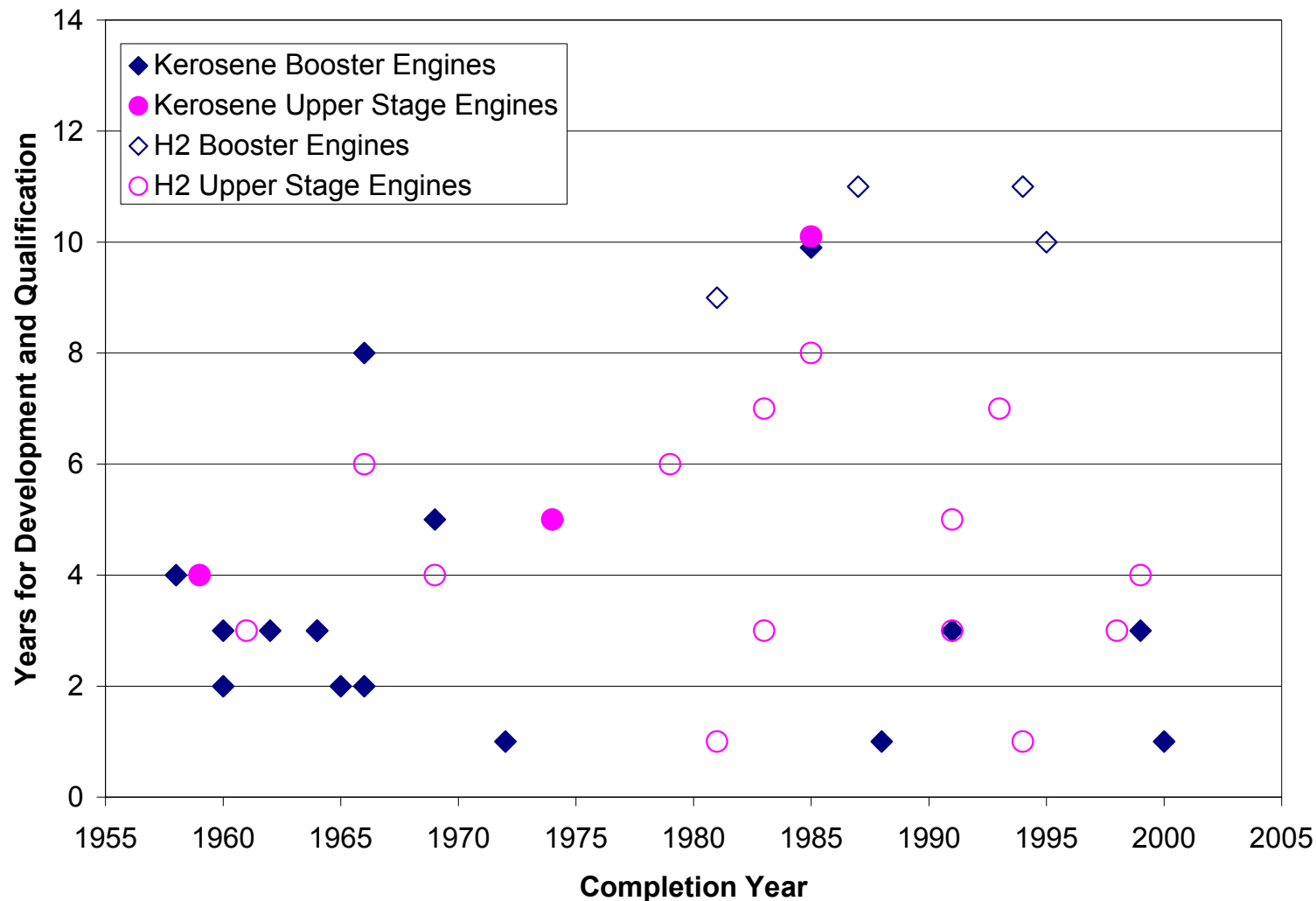
George, D.; "Chemical Propulsion: How To Make It Low Cost," presented at Highly Reusable Space Transportation Meeting, 25-27 July 1995.



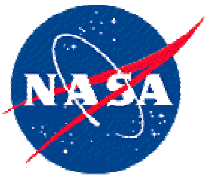


# Survey of LOX/RP and LOX/LH Engine Development Programs

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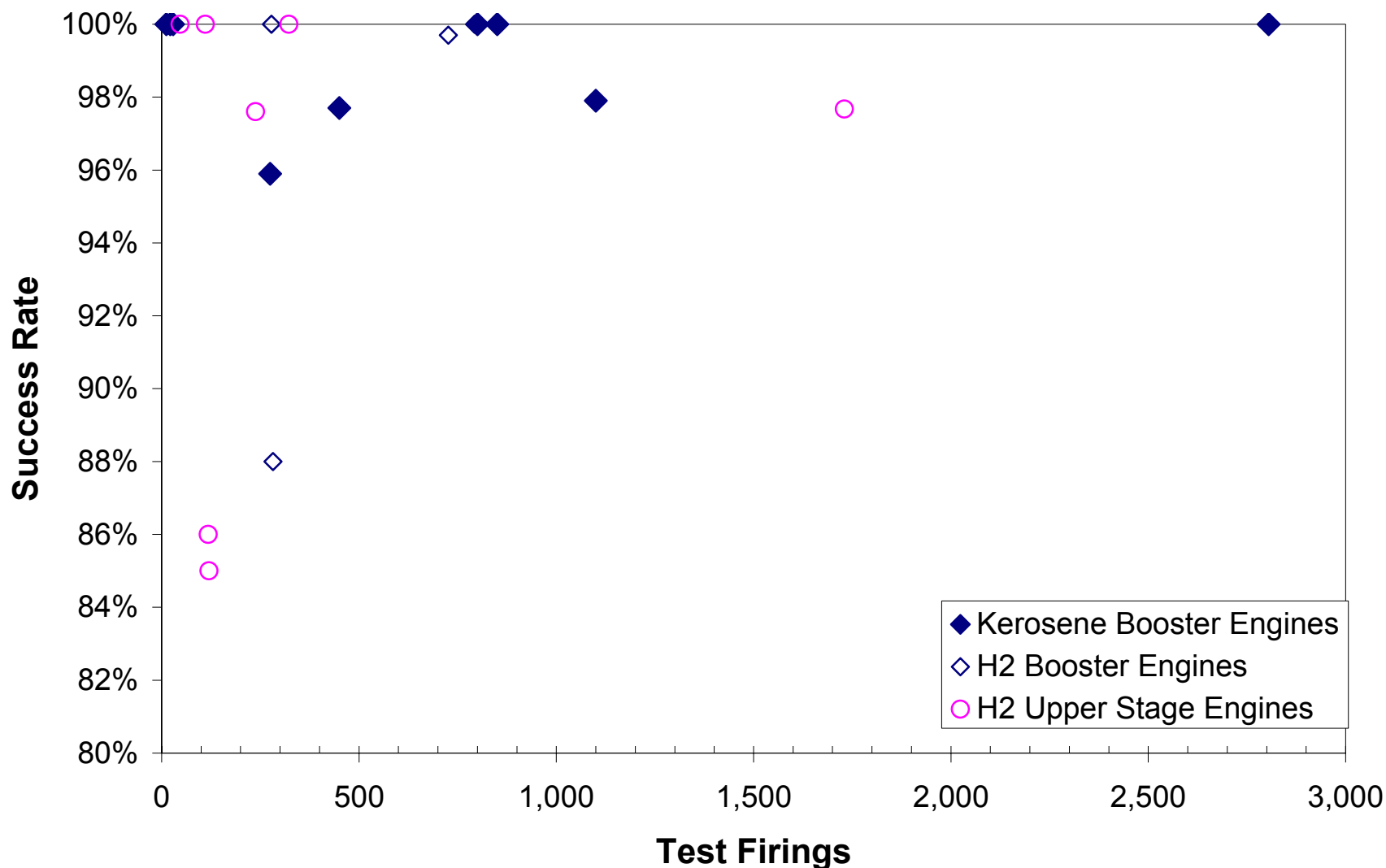


- Emdee, J., "A Survey of Development Test Programs for Hydrogen Oxygen Rocket Engines," AIAA Paper No. 2001-0749.
- Emdee, J., "A Survey of Development Test Programs for LOX/Kerosene Liquid Rocket Engines," AIAA Paper No. 2001-3985.

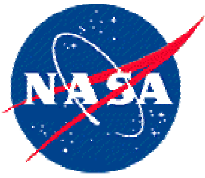


# Effect on Engine Flight Success Rate

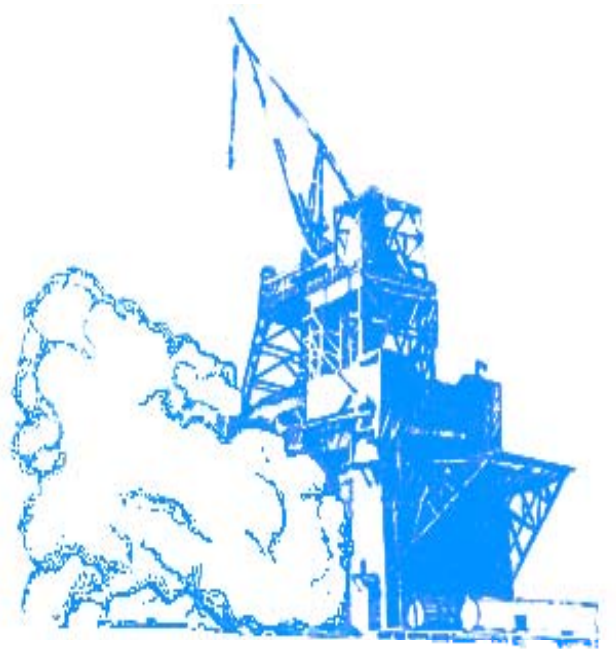
*AIAA LRE Course*

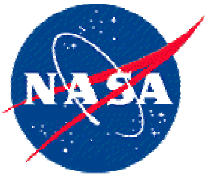


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- Emdee, J., "A Survey of Development Test Programs for LOX/Kerosene Liquid Rocket Engines," AIAA Paper No. 2001-3985. 10



## ***REPRESENTATIVE TEST CAMPAIGNS***





## Test Facility Challenges – *Components, Engines, Stages*

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- Stage/Vehicle Testing
  - Complex
    - Self Contained
    - Transfer Systems
- Engine Testing
  - More Complexity
    - Engine Self Contained
    - Propellant Systems on Stand
    - Transfer Systems
- Component Testing
  - More Complexity
    - Facility Emulates Engine Parameters
    - High Pressures
    - High Flowrates
    - Extremely Fast Controls



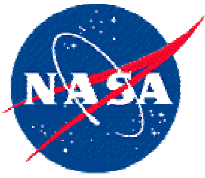
Space Shuttle  
Vehicle  
(External Tank)



Space Shuttle  
Main Engine



Turbopump  
Component



# A Survey of Test Engine Test Campaigns

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	<b><u>SSME</u></b> (Boost)	<b><u>F-1</u></b> (Boost)	<b><u>RS-68</u></b> (Boost)	<b><u>J-2</u></b> (U/S)	<b><u>RL-10A-1</u></b> (U/S)	<b><u>LMDE</u></b> (Lander)
<b>Thrust</b>	<b>500 Klbf</b>	<b>1.5 Mlbf</b>	<b>700 Klbf</b>	<b>250 Klbf</b>	<b>15 Klbf</b>	<b>10 Klbf</b>
<b>Hot-Fire Test Seconds Prior to First Flight</b>	<b>110,000 s</b>	<b>250,000 s</b>	<b>**11,000 s</b> (i/w)	<b>120,000 s</b>	<b>71,000 s</b>	<b>149,000 s</b>
<b>Hot-Fire Test Seconds After First Flight</b>	<b>~750,000 s*</b> (& counting)	<b>30,000 s</b>	<b>6,810 s</b>	<b>in-work</b> (i/w)	<b>Upgraded to</b> <b>RL-10A-3</b>	<b>N/A</b>
<b>Hot-Fire Tests Prior to First Flight</b>	<b>726</b>	<b>2805</b>	<b>188</b>	<b>1730</b>	<b>707</b>	<b>2809</b>
<b>Years of Devt.</b>	<b>9</b>	<b>8</b>	<b>5 - 6</b>	<b>6</b>	<b>3</b>	<b>5</b>
<b>Missions Flown</b>	<b>113</b>	<b>~15</b>	<b>3</b>	<b>~15</b>	<b>i/w</b>	<b>6</b> (Apollo 11,12,14-17)
<b>Vehicle</b>	<b>Shuttle</b>	<b>Saturn V</b>	<b>Delta IV</b>	<b>Saturn V</b>	<b>Various</b>	<b>Saturn V</b>

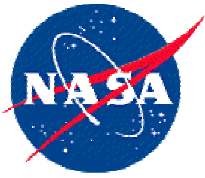
\*SSME Flight Seconds (~150,000 s) not counted

\*\*RS-68 Pre-flight Seconds (in-work): ~19500 s total (~11000 s at SSC)

For many of the above:

testing was performed at a variety of locations

- Emdee, J., "A Survey of Development Test Programs for Hydrogen Oxygen Rocket Engines," AIAA Paper No. 2001-0749.
- Emdee, J., "A Survey of Development Test Programs for LOX/Kerosene Liquid Rocket Engines," AIAA Paper No. 2001-3985.
- Elverum, G. et al., "The Descent Engine for the Lunar Module," AIAA Paper No. 67-521.



# Testing to Enhance Reliability (LOX/LH)

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## Booster Engines

Designation	Time from Program Start to Qualification	Engine Life (firings / secs)	Burn Time (secs)	Feasibility			Development including stage firings			Qualification including stage firings			Total Development and Qualification including stage firings			Flight Success Rate
				Engines	Firings	Seconds	Engines	Firings	Seconds	Engines	Firings	Seconds	Engines	Firings	Seconds	
LE-7	11 years ('83-'94)	- / 1720	350	2	-	-	9	-	-	5	-	-	14	282	15,639	88.0%
RD-0120	11 years ('76-'87)	4 / 2000	460	-	-	-	-	-	-	3	-	-	90	793	163,000	100.0%
SSME <sup>†</sup>	9 years ('72-'81)	55 / 27,000	520	0	0	0	16+	627	77,135	4+	99	33,118	20+	726	110,253	99.7%
Vulcain	10 years ('85-'95)	20 / 6000	575	0	0	0	12+	-	-	2	-	-	14+	278	87,000	100.0%

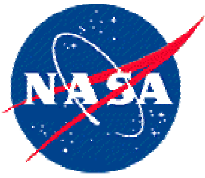
<sup>†</sup> SSME includes production up to 1<sup>st</sup> flight

## Upper Stage Engines

Designation	Time from Program Start to Qualification	Engine Life (firings / secs)	Burn Time (secs)	Feasibility			Development including stage firings			Qualification including stage firings			Total Development and Qualification including stage firings			Flight Success Rate
				Engines	Firings	Seconds	Engines	Firings	Seconds	Engines	Firings	Seconds	Engines	Firings	Seconds	
HM7A	6 yrs ('73-'79)	-	570	-	-	-	-	-	-	-	-	-	11	-	25,000	90.0%
HM7B	3 yrs ('80-'83)	-	745	-	-	-	-	-	-	-	-	-	10	-	-	96.6%
J-2	6 yrs ('60-'66)	30 / 3750	450	-	-	-	36	1,700	116,000	2	30	3,807	38	1,730	120,000	97.7%
J-2S*	4 yrs ('65-'69)	30 / 3750	450	1	-	10,756	6	273	30,858	Development only			Development only			N/A
LE-5	8 yrs ('77-'85)	-	600	3	54	2,587	5	188	13,414	3	134	14,292	8	322	27,706	100.0%
LE-5A	5 yrs ('86-'91)	14 / 2920	535	0	0	0	2	66	6,918	2	52	9,238	4	118	16,156	86.0%
LE-5B	4 yrs ('95-'99)	16 / 2236	534	1	8	237	1	23	1,077	4	79	11,963	5	102	13,040	N/A
RL10A-1	3 yrs ('58-'61)	-	380	-	-	-	>230	-	-	-	-	-	>230	707	71,036	N/A
RL10A-3-3A	1 yr ('80-'81)	23 / 5800	600	0	0	0	4+	214	18,881	1	24	5,864	5+	238	24,745	97.6%
RL10A-4	3 yrs ('88-'91)	27 / 4000	400	3+	51	8,321	2+	73	15,055	1	38	5,265	3+	111	20,320	100.0%
RL10A-4-1	1 yr ('94)	28 / 3480	400	0	0	0	1	5	2,068	1	42	3,683	2	47	5,751	100.0%
RL10B-2	3 yrs ('95-'98)	15 / 3500	700	1	119	1,701	3+	125	11,605	1	30	4,044	4	155	15,649	50.0%
YF-73	7 yrs ('76-'83)	-	800	-	-	-	-	-	-	-	-	-	-	120	30,000	85.0%
YF-75	7 yrs ('86-'93)	-	500	-	-	-	-	-	-	-	-	-	-	-	28,000	100.0%

\* J-2S did not enter qualification due to program cancellation. Data included for comparative purposes only

- Emdee, J., "A Survey of Development Test Programs for Hydrogen Oxygen Rocket Engines," AIAA Paper No. 2001-0749.



# Testing to Enhance Reliability (LOX/RP)

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## Booster Engines

Designation	Time from Program Start to Qualification	Engine Life (firings / secs)	Nominal Burn Time (secs)	Feasibility			Development including stage firings			Qualification including stage firings			Total Development and Qualification including stage firings			Flight Success Rate
				Engines	Firings	Seconds	Engines	Firings	Seconds	Engines	Firings	Seconds	Engines	Firings	Seconds	
F-1	8 yrs ('59-'66)	20 / 2250	165	-	-	-	-	-	-	2	34	>2255	56	2805 <sup>†</sup>	252,958 <sup>†</sup>	100.0%
H-1 165K	2 yrs ('58-'60)	-	165	-	-	-	-	-	-	-	-	-	17	85	-	100.0%
H-1 188K	3 yrs ('60-'62)	-	165	-	-	-	-	-	-	-	-	-	27	1,100	-	97.9%
H-1 200K	2 yrs ('63-'65)	-	165	-	-	-	-	-	-	-	-	-	48	1,700	-	N/A
H-1 205K	2 yrs ('65-'66)	-	165	-	-	-	-	-	-	-	-	-	16	800	-	100.0%
LR87-AJ-1	4 yrs ('55-'58)	-	138	-	-	-	-	-	-	1	46	3,579	-	-	-	-
MA-3 Booster	3 yrs ('58-'60)	-	-	-	-	-	-	-	-	3	44	-	-	-	-	98.2%
MA-3 Sustainer	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	96.4%
MA-5 Booster	3 yrs ('61-'64)	-	174	-	-	-	-	-	-	-	-	-	-	-	-	98.7%
MA-5 Sustainer	3 yrs ('61-'64)	-	266	-	-	-	-	-	-	-	-	-	-	-	-	98.7%
MA-5A Booster	3 yr ('88-'91)	-	170	0	0	0	0	0	0	1	29	748	1	29	748	100.0%
MA-5A Sustainer	3 yr ('88-'91)	-	289	0	0	0	0	0	0	1	12	716	1	12	716	100.0%
NK-15/NK-15B	5 yrs ('64-'69)	1 / 110	110	-	-	-	-	-	-	-	-	-	199	450	40,200	97.7%
NK-33 / NK-43	5 yrs ('69 - '74)	3 / 365	110	-	-	-	-	-	-	9	39	4,875	101	350	61,651	N/A
RD-171	10 yrs ('75-'85)	-	150	-	346	19,685	-	-	-	-	-	-	~80	~275	~25,000	95.9%
RD-180 (Atlas III)	3 yrs ('96-'99)	-	186	-	-	-	8+	70	10,956	4+	25	4,618	11+	95	15,574	100.0%
RD-180 (Atlas V)	1 yr ('99-'00)	-	230	-	-	-	3+	19	3,420	1	5	1,024	4+	24	4,444	N/A
RS-27	1 yr ('72)	-	265	-	-	-	-	-	-	-	-	-	-	-	-	100.0%
RS-27A	1 yr ('88)	-	265	0	0	0	0	0	0	1	22	-	1	22	-	100.0%

† = includes production due to lack of further information

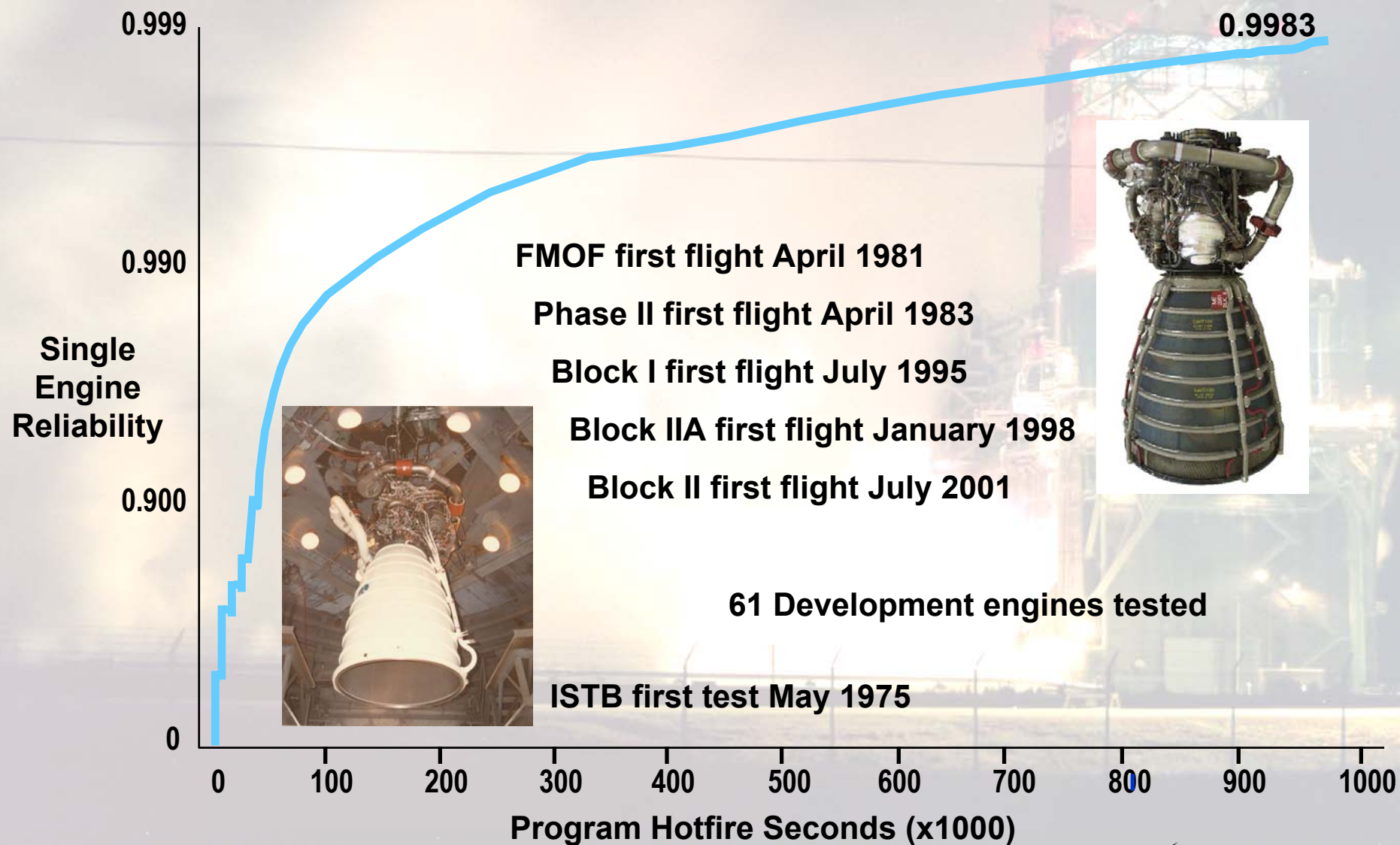
## Upper Stage Engines

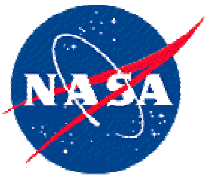
Designation	Time from Program Start to Qualification	Engine Life (firings / secs)	Burn Time (secs)	Feasibility			Development including stage firings			Qualification including stage firings			Total Development and Qualification including stage firings			Flight Success Rate
				Engines	Firings	Seconds	Engines	Firings	Seconds	Engines	Firings	Seconds	Engines	Firings	Seconds	
LR91-AJ-1	4 yrs ('55-'59)	-	225	-	-	-	-	-	-	1	39	2,933	-	-	-	-
NK-43	5 yrs ('69 - '74)	3 / 365	-	-	-	-	-	-	-	-	-	-	5	13	969	-
RD-120	10 yrs ('75-'85)	-	315	-	-	-	-	-	-	-	-	-	-	-	-	94.9%

- Emdee, J., "A Survey of Development Test Programs for LOX/Kerosene Liquid Rocket Engines," AIAA Paper No. 2001-3985.

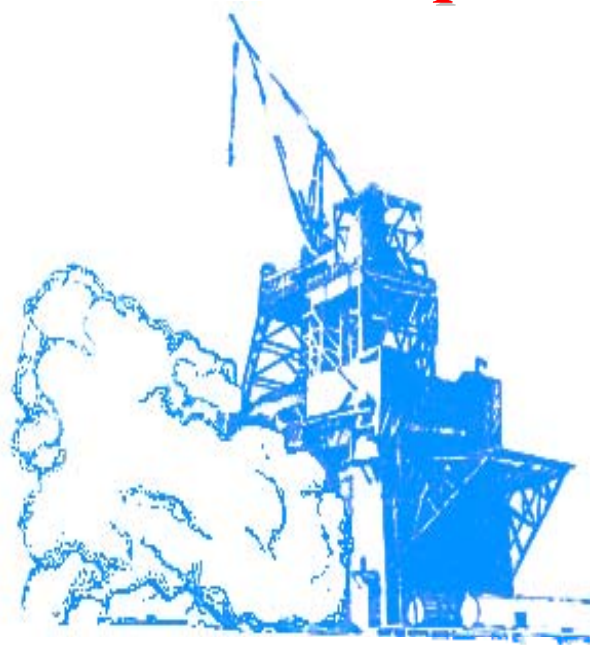


# Test Demonstrated Reliability





# ***OVERVIEW OF TEST FACILITIES FOR LIQUID PROPULSION TESTING (representative capabilities)***





# Rocket Propulsion Test Sites

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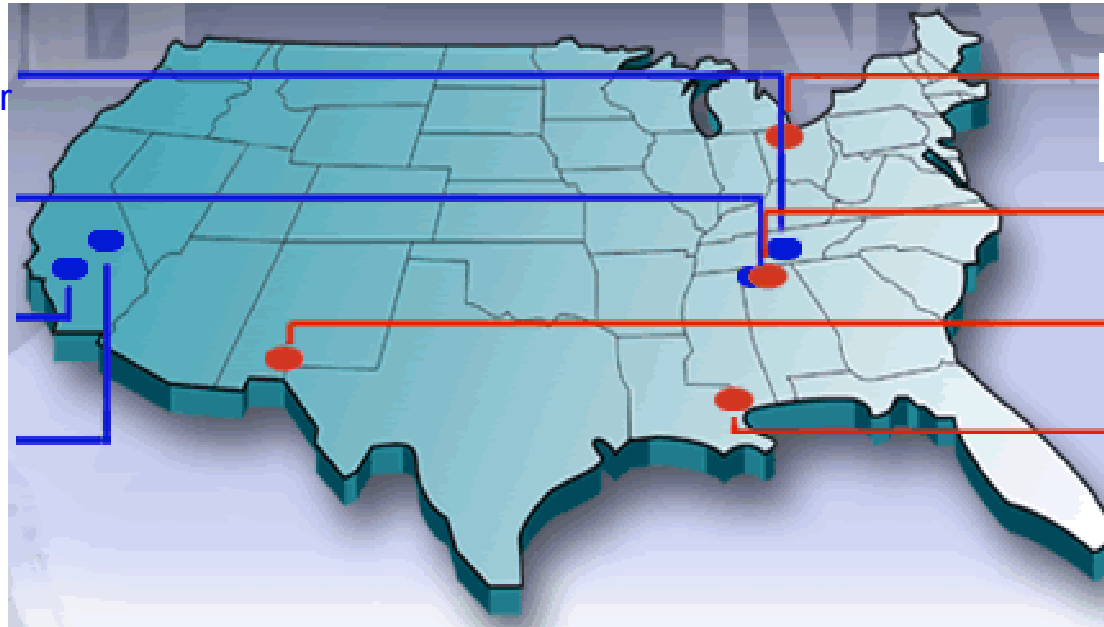
## DoD Sites

Arnold Engineering  
Development Center

Redstone Arsenal

Edwards AFB,  
AFRL

Naval Warfare,  
China Lake



## NASA Sites

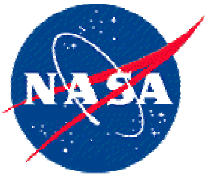
Glenn Research Center  
Plum Brook Station

Marshall Space  
Flight Center

White Sands  
Test Facility

Stennis Space Center

<https://rockettest.ssc.nasa.gov>



# Test Capability Figures of Merit

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- Component Testing Capability
  - Thrust Scale, Propellants, Pressure
- Engine Testing
  - Thrust Scale, Propellants, Duration
- Stage Testing
  - Thrust Scale, Propellants, Pressure



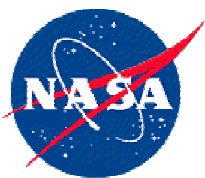
Pressure → ultra-low (vac demo) and ultra-high (for components dev)

Duration → extended duration capability sufficient to run mission profile

Propellants → cryo, or non-cryo, hypergol, storables, etc.

Thrust Scale → appropriate thrust level infrastructure for test article size/thrust



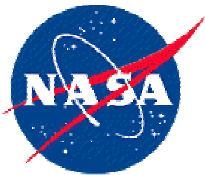


# SSC and Surrounding Buffer Zone

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# Stennis Space Center Test Facilities

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**A-1 ... Large Scale Devt. & Cert ... A-2**



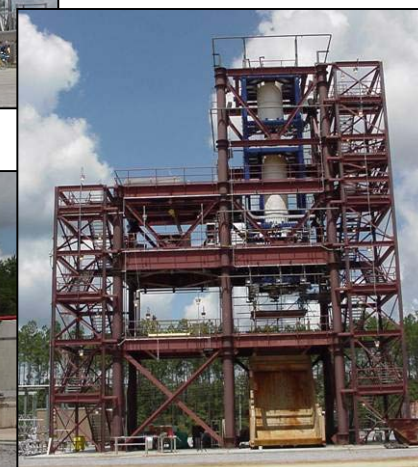
**E-1 Stand**

High Press, Full Scale  
(Battleship, Proto h/w)



**E-2**

High Press  
Mid-Scale  
& Subscale

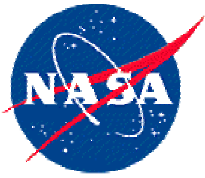


**B-1/B-2 ... Full Scale Devt. & Cert**

**E-3**

High Press  
Small-Scale  
Subscale



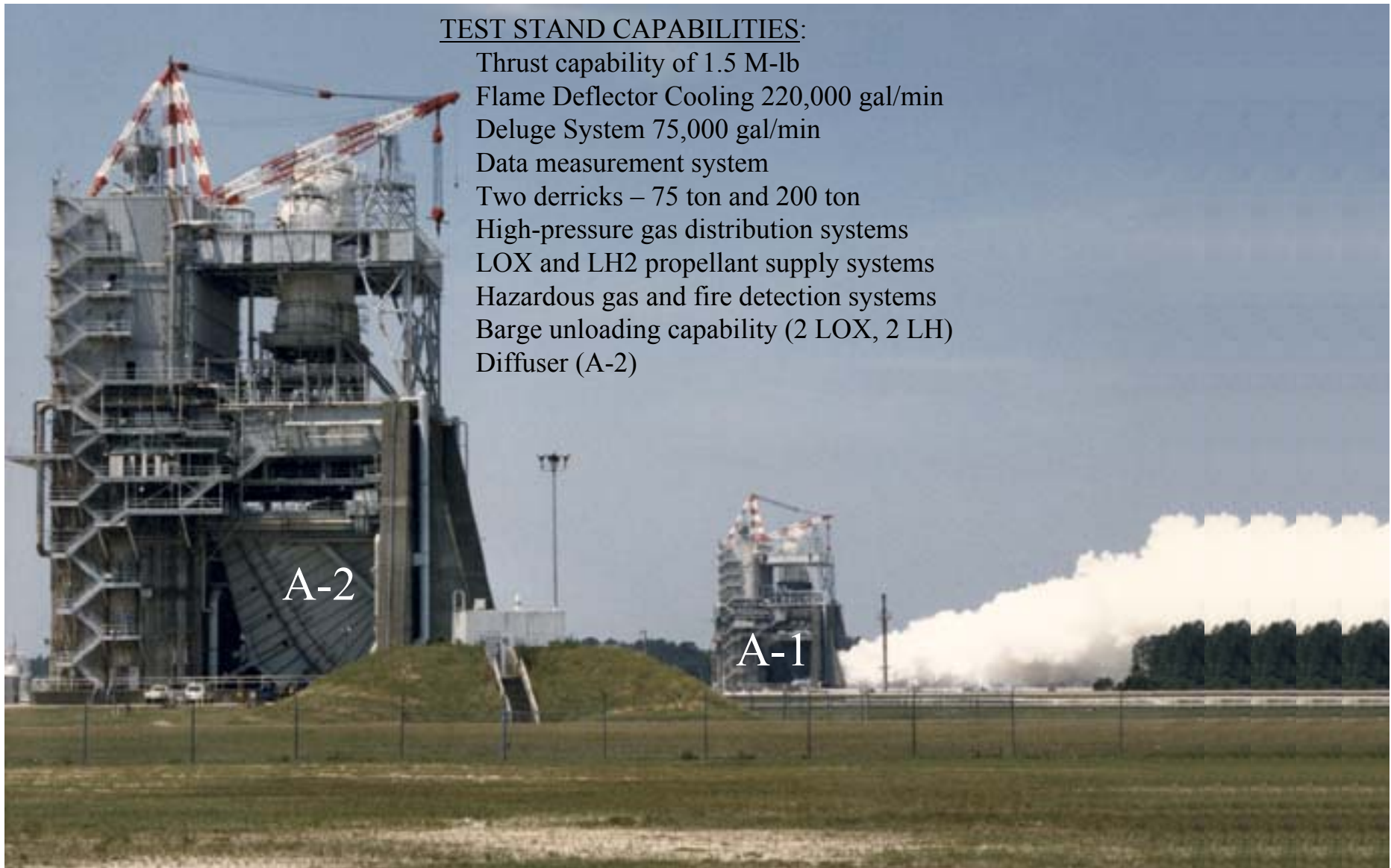


# Stage & Engine Testing – SSC A Complex

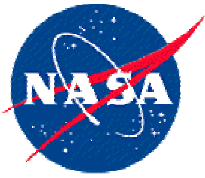
*AIAA LRE Course*

## TEST STAND CAPABILITIES:

- Thrust capability of 1.5 M-lb
- Flame Deflector Cooling 220,000 gal/min
- Deluge System 75,000 gal/min
- Data measurement system
- Two derricks – 75 ton and 200 ton
- High-pressure gas distribution systems
- LOX and LH2 propellant supply systems
- Hazardous gas and fire detection systems
- Barge unloading capability (2 LOX, 2 LH)
- Diffuser (A-2)







# Space Shuttle Main Engine Test

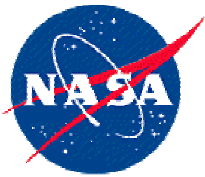
*AIAA LRE Course*



SSC A-1 Test Stand

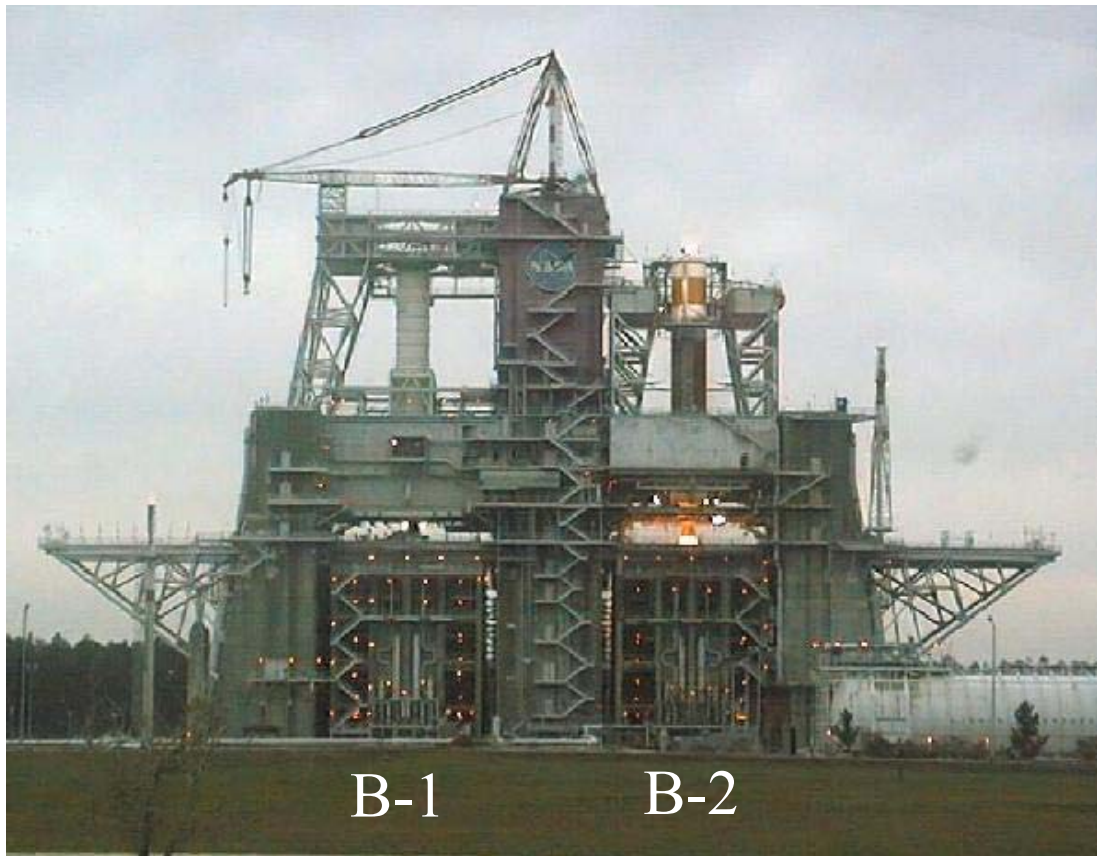
Space Shuttle Engine





# Stage and Engine Testing – SSC B Complex

*AIAA LRE Course*



B-1

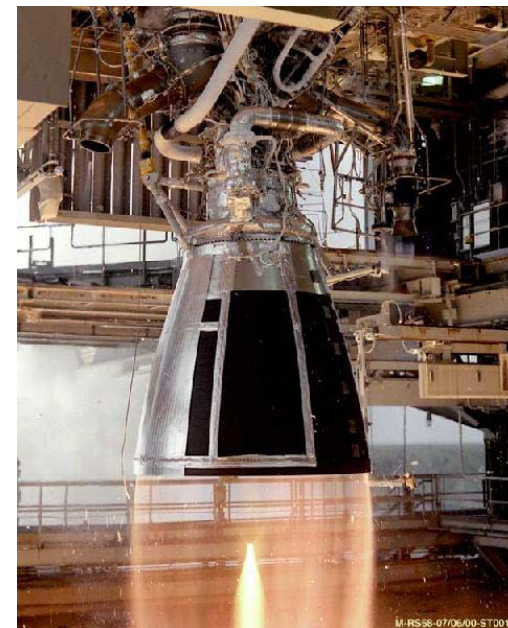
B-2

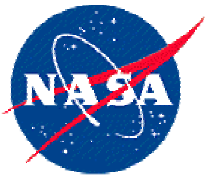
B-2 Test of Delta IV Common Booster Core

B-1 Test of Delta IV RS-68

## TEST STAND CAPABILITIES:

- Thrust capability of 13 M-lb
- Flame Deflector Cooling 330,000 gal/min
- Deluge System 123,000 gal/min
- Data measurement system
- Two derricks – 175 ton and 200 ton
- High-pressure gas distribution systems
- LOX and LH2 propellant supply systems
- Hazardous gas and fire detection systems
- Barge unloading capability (3 LOX, 3 LH)





# Component and Engine Testing - SSC E-1 Test Stand

*AIAA LRE Course*

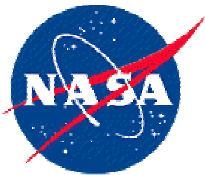


## General Pressure Capabilities

- $\text{LO}_2/\text{LH}_2 \sim 8,500$  psi
- RP  $\sim 8500$  psi (Ready 1/06)
- GN/GH  $\sim 15,000$  psi
- Ghe  $\sim 10,000$  psi

- E1 Cell 1
  - Primarily Designed for Pressure-Fed  $\text{LO}_2/\text{LH}_2/\text{RP}$  & Hybrid-Based Test Articles
  - Thrust Loads up to  $750\text{K lb}_f$  (horizontal)
- E1 Cell 2
  - Designed for  $\text{LH}_2$  Turbopump & Preburner Assembly Testing
  - Thrust Loads up to  $60\text{K lb}_f$
- E1 Cell 3
  - Designed for  $\text{LO}_2$  Turbopump, Preburner Assembly Testing &  $\text{LOX/LH}$  Engine Testing
  - Thrust Loads up to  $750\text{K lb}_f$





## Mid-Scale Component/Engine Testing - SSC E-2

*AIAA LRE Course*



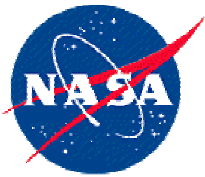
### •E2 Cell 1

- Primarily Designed for Pressure-Fed  $\text{LO}_2/\text{RP1}$  Based Test Articles
- Thrust Loads up to 100K  $\text{lb}_f$  (horizontal)
- $\text{LO}_2/\text{RP1}$  ~ 8500 psia
- GN/GH ~ 15000 psia
- Hot GH (6000 psia/1300 F)



### •E2 Cell 2

- Designed for  $\text{LO}_2/\text{H}_2\text{O}_2/\text{RP1}$  Engine/Stage Test Articles
- Loads up to 150K  $\text{lb}_f$



# Altitude Simulation Capability for Propulsion

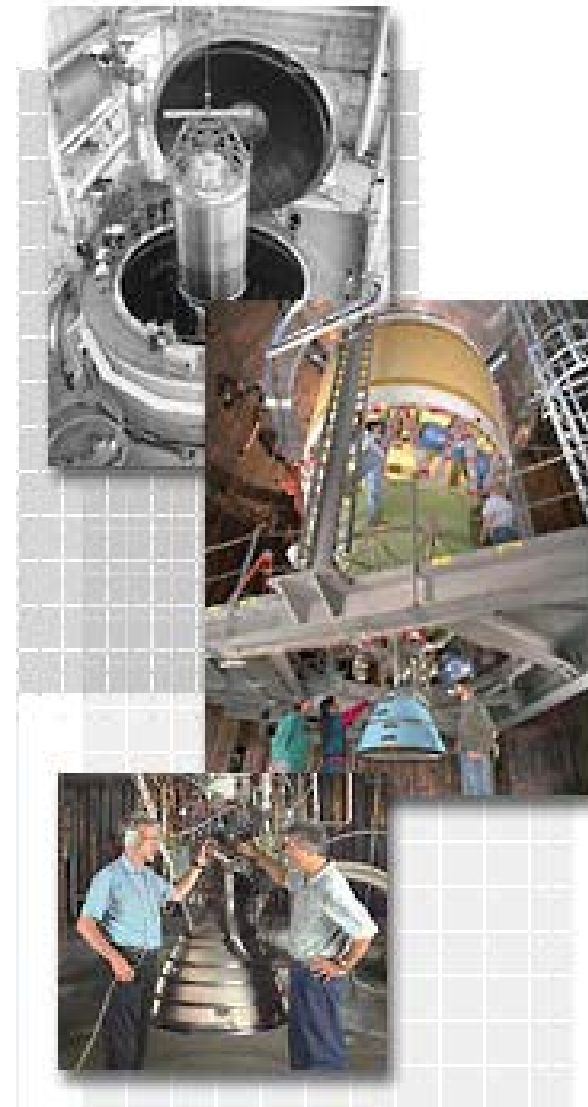
*AIAA LRE Course*

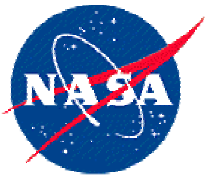
## Spacecraft Propulsion Research Facility (Plum Brook Station B-2)

B-2 is a one-of-a-kind facility that tests full-scale upper-stage launch vehicles and rocket engines under simulated high-altitude conditions.  
(e.g. Delta LV Upper Stage – LOX/LH)

**Purpose:** To test an engine or vehicle that is exposed for indefinite periods to low ambient pressures, low background temperatures, and dynamic solar heating simulating the environment hardware encounters during orbital or interplanetary travel.

- certification and baseline tests of unique flight hardware
- capability for long duration space environment soaking
- spacecraft subsystem and full system integration testing





## Altitude Simulation (cont.)

*AIAA LRE Course*



*Rocket Engine Firing Inside Vacuum Test Cell*

### White Sands Test Facility

- Eight engine/system test stands (5 vacuum cells)
- Long-duration high-altitude simulation
  - SSME OMS, RCS
- Hypergolic (Hydrazines, NTO) and cryogenic liquid rocket systems
  - Small to medium thrust levels

For details see: <https://rockettest.ssc.nasa.gov>

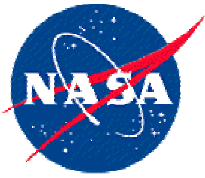


*Propulsion Test Area 400*



*Altitude Simulation System Operation for Rocket Engine Tests*





# Advanced Propulsion Test Capability

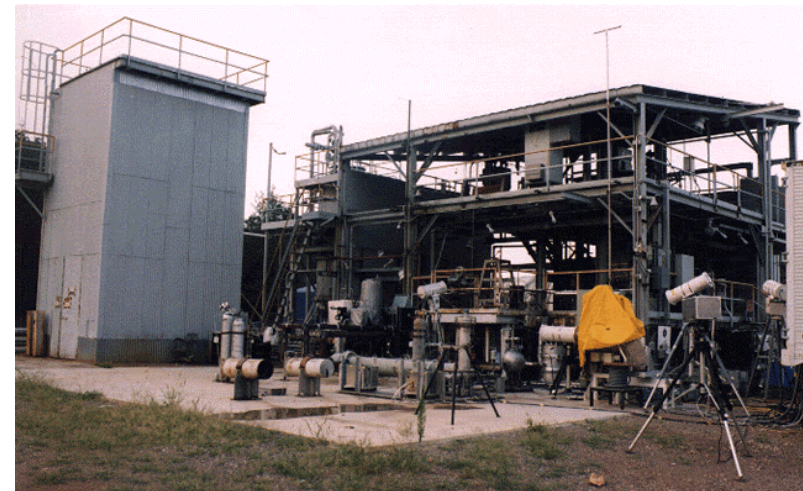
*AIAA LRE Course*

## Test Stand 115, 116 (Marshall Space Flight Center)



### TF 115

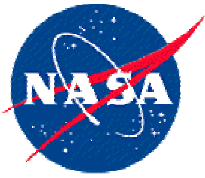
- Ambient Test Capability
- Propellants: GH<sub>2</sub>, LH<sub>2</sub>, LOX, LCH<sub>4</sub> & RP-1
- Maximum Thrust - 4 K lbf
- The compact size of the facility makes it ideal for testing subscale components.



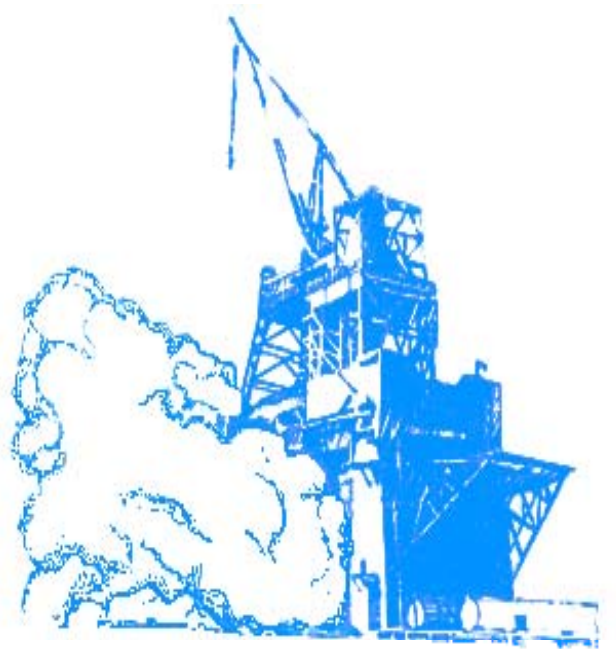
### TF 116

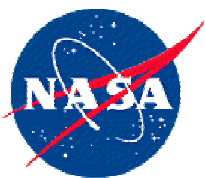
- Multiple Position Facility
- Ambient Test Capability
- Designed to test High Pressure Combustion Devices, Engines/System, Cryogenic Propellant Systems





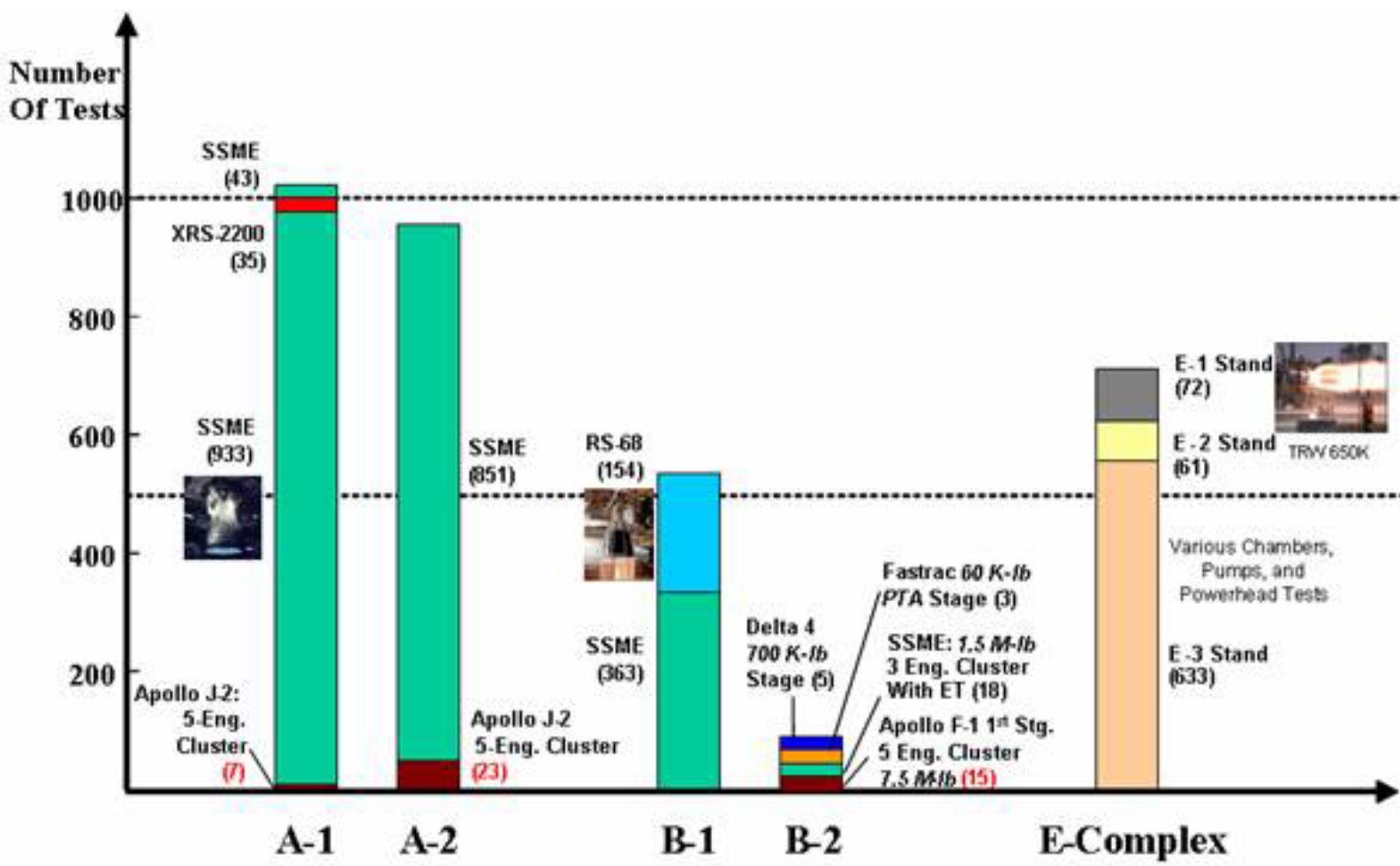
## ***STATISTICS (HISTORICAL) OF LRE TESTING***



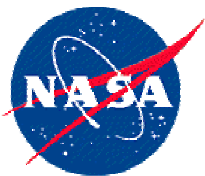


# SSC Testing History (1966 – 2004)

*AIAA LRE Course*

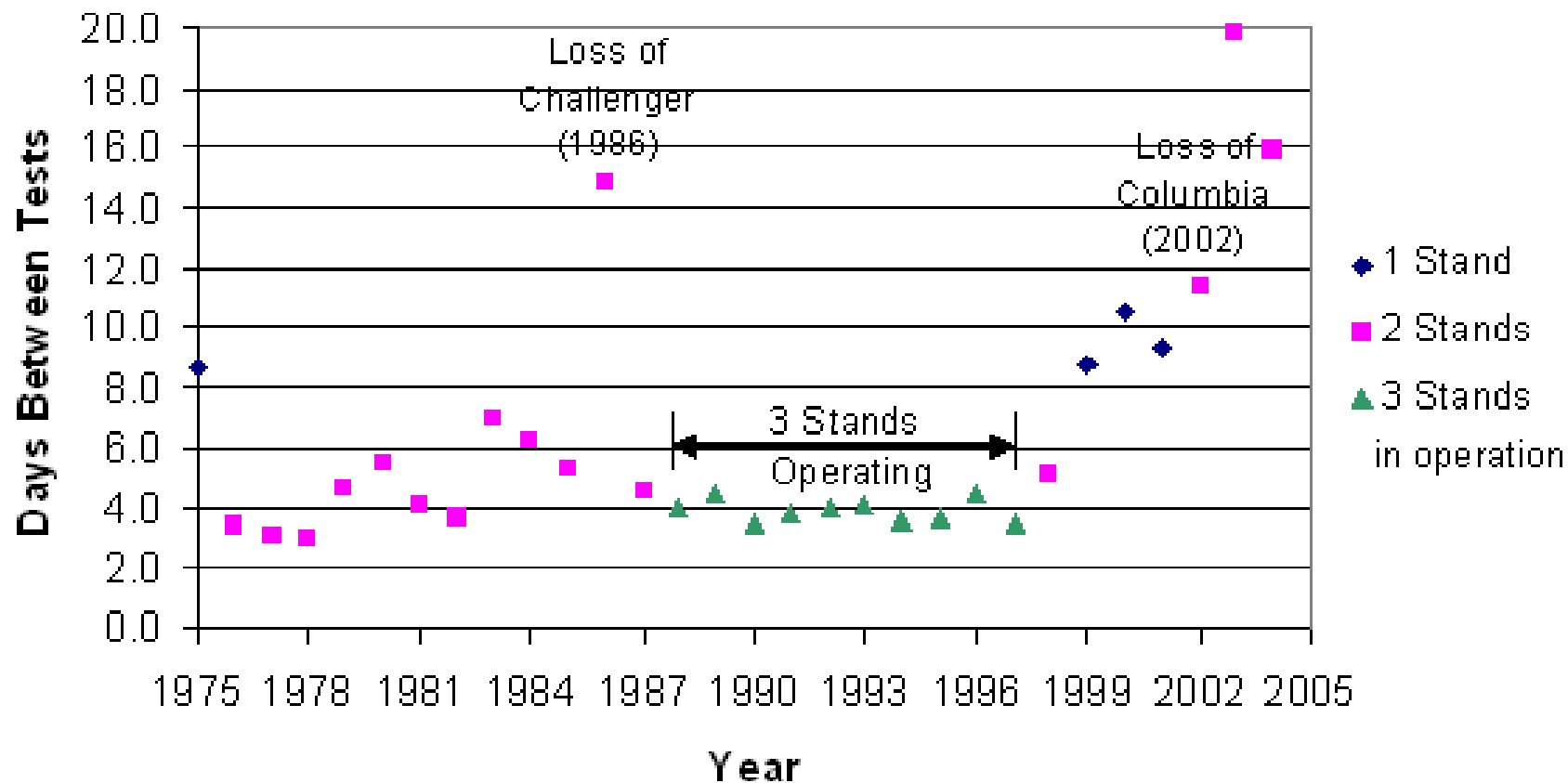


Ref: Kirchner, C., Morgan, J., and Rahman, S., "SSC Rocket Propulsion Testing Major Statistics," SSC Internal Memo, 2005.

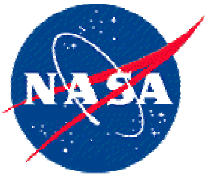


# SSC Test Rate for SSME (1976 – 2004)

AIAA LRE Course



Ref: Kirchner, C., Morgan, J., and Rahman, S., "SSC Rocket Propulsion Testing Major Statistics," SSC Internal Memo, 2005.



# Overview of US Engine Test Campaigns

AIAA LRE Course

	<b><u>SSME</u></b> (Boost)	<b><u>F-1</u></b> (Boost)	<b><u>RS-68</u></b> (Boost)	<b><u>J-2</u></b> (U/S)	<b><u>RL-10A-1</u></b> (U/S)	<b><u>LMDE</u></b> (Lander)
<b>Thrust</b>	<b>500 Klbf</b>	<b>1.5 Mlbf</b>	<b>700 Klbf</b>	<b>250 Klbf</b>	<b>15 Klbf</b>	<b>10 Klbf</b>
<b>Hot-Fire Test Seconds Prior to First Flight</b>	<b>110,000 s</b>	<b>250,000 s</b>	<b>**11,000 s (i/w)</b>	<b>120,000 s</b>	<b>71,000 s</b>	<b>149,000 s</b>
<b>Hot-Fire Test Seconds After First Flight</b>	<b>~750,000 s* (&amp; counting)</b>	<b>30,000 s</b>	<b>6,810 s</b>	<b>in-work (i/w)</b>	<b>Upgraded to RL-10A-3</b>	<b>N/A</b>
<b>Hot-Fire Tests Prior to First Flight</b>	<b>726</b>	<b>2805</b>	<b>188</b>	<b>1730</b>	<b>707</b>	<b>2809</b>
<b>Years of Devt.</b>	<b>9</b>	<b>8</b>	<b>5 - 6</b>	<b>6</b>	<b>3</b>	<b>5</b>
<b>Missions Flown</b>	<b>113</b>	<b>~15</b>	<b>3</b>	<b>~15</b>	<b>i/w</b>	<b>6</b> (Apollo 11,12,14-17)
<b>Vehicle</b>	<b>Shuttle</b>	<b>Saturn V</b>	<b>Delta IV</b>	<b>Saturn V</b>	<b>Various</b>	<b>Saturn V</b>

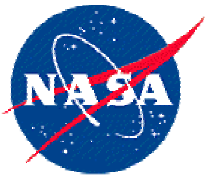
\*SSME Flight Seconds (~150,000 s) not counted

\*\*RS-68 Pre-flight Seconds (in-work): ~19500 s total (~11000 s at SSC)

For many of the above:

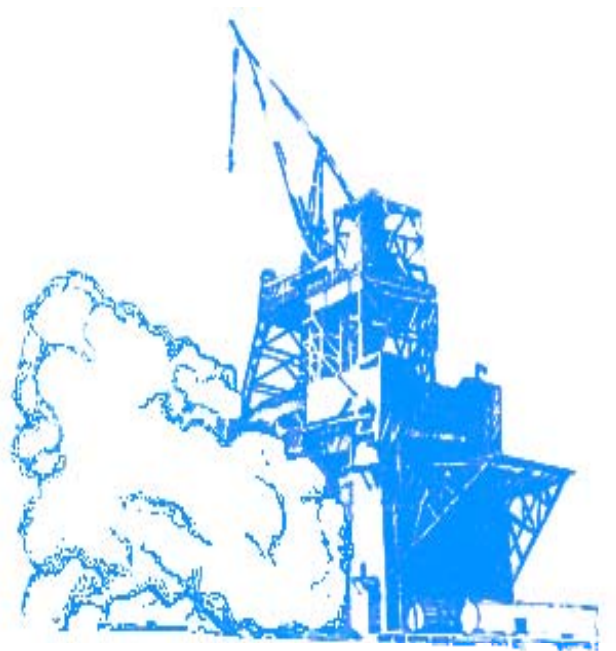
testing was performed at a variety of locations

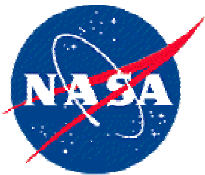
- Emdee, J., "A Survey of Development Test Programs for Hydrogen Oxygen Rocket Engines," AIAA Paper No. 2001-0749.
- Emdee, J., "A Survey of Development Test Programs for LOX/Kerosene Liquid Rocket Engines," AIAA Paper No. 2001-3985.
- Elverum, G. et al., "The Descent Engine for the Lunar Module," AIAA Paper No. 67-521.



# ***TEST PROJECT ENABLERS***

## ***- Engineering Tools, Operations, Processes, Infrastructure -***





# Test Project Process

AIAA LRE Course

- Life cycle of a typical test project

## Test Project Formulation

(requirements, trade-offs,  
schedule & cost, upgrades needed )



INPUTS



## Special Test Equipment Design & Engineering

(mechanical,  
electrical, data)



INPUTS



## Hardware & Software Modifications



INPUTS

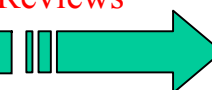


## Operational Activities

(procedure mods, activations,  
test operations)



Test Data Reviews



INPUTS

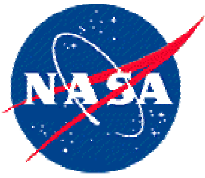


## Demobilization And Project Closeout, (and potential follow-on)



Test Final Report  
& T/A Ship





# State of the Art Test Stand Software

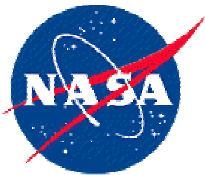
*AIAA LRE Course*

- Configuration Management
  - Automated Electronic Process
  - Test Site Drawings
  - Future – Project Requirements, Component Specs
- Data Acquisition and Controls Lab
  - Off-Line Testing
    - Test Software
    - Electrical Hardware



*Data Acquisition and Control Systems Lab  
(DACS Lab)*



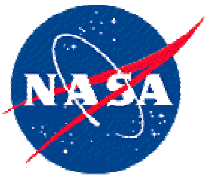


# State of the Art Test Stand Hardware

*AIAA LRE Course*

- Cooperative Agreement Procurements
  - Large, High Pressure Cryogenic Valves
  - Quick Responding, High Pressure RTD's





# SSC Test Support Infrastructure

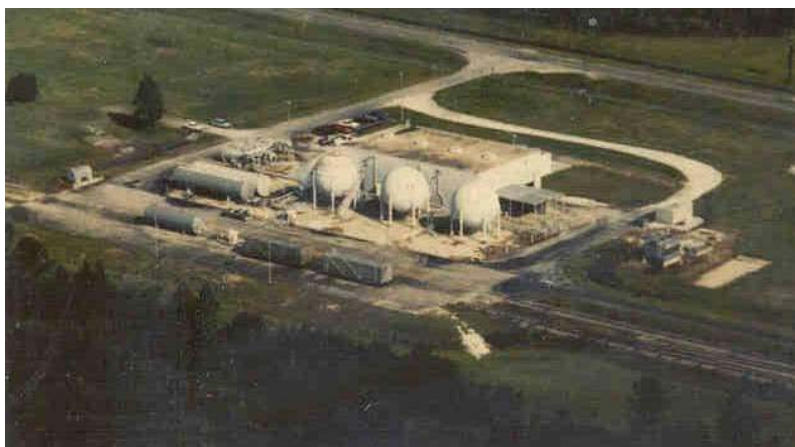
*AIAA LRE Course*



Cryogenic Propellant Storage Facility  
Six (6) 100,000 Gallons LOX Barges  
Three (3) 240,000 Gallons LH Barges



High Pressure Industrial Water (HPIW)  
330,000 gpm



High Pressure Gas Facility (HPGF)  
(GN, GHe, GH, Air)

## Additional Support

### -Laboratories

- Environmental
- Gas and Material Analysis
- Measurement Standards and Calibration

### - Shops

### - Utilities



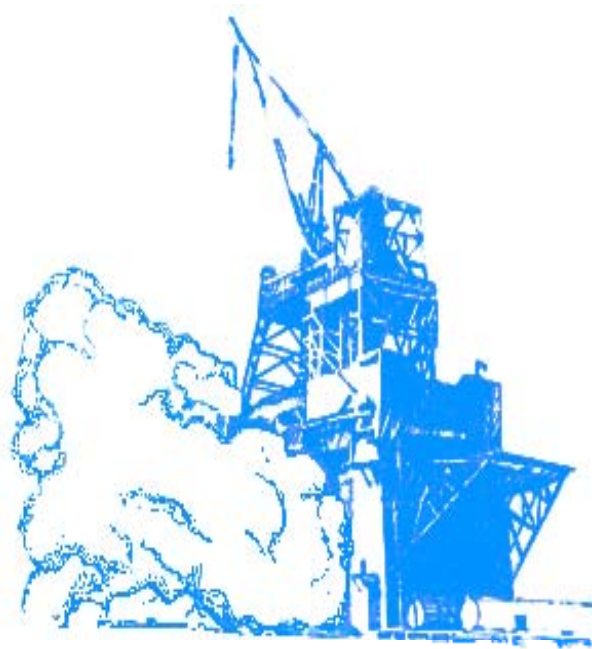
# Test Technology Advancements

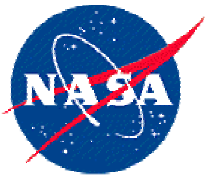
*AIAA LRE Course*

- Advanced Sensors and Measurement Systems
  - Smart Sensor testbed, and integrated sensor suites
  - Integrated System Health Management testbed
- Advanced Data Acquisition and Controls
  - Closed loop fast feedback controls
  - System simulation integrated with Facility Controls
- Mechanical Components and Systems
  - Comprehensive modeling and simulation from Propellant tank to Test Article
  - Computational fluid dynamics solutions to complex internal flows (tanks, valves)
  - High performance test stand valves (15000 psi working pressures, rapid actuation)
- Plume Effects Prediction and Monitoring
  - Non-intrusive diagnostics (species, acoustics, thermal)
  - CFD analysis of plume effects with Benchmarked Codes



## ***NON-NASA TEST CAPABILITY - DOD, Commercial, University -***





# Rocket Propulsion Test Sites

*AIAA LRE Course*

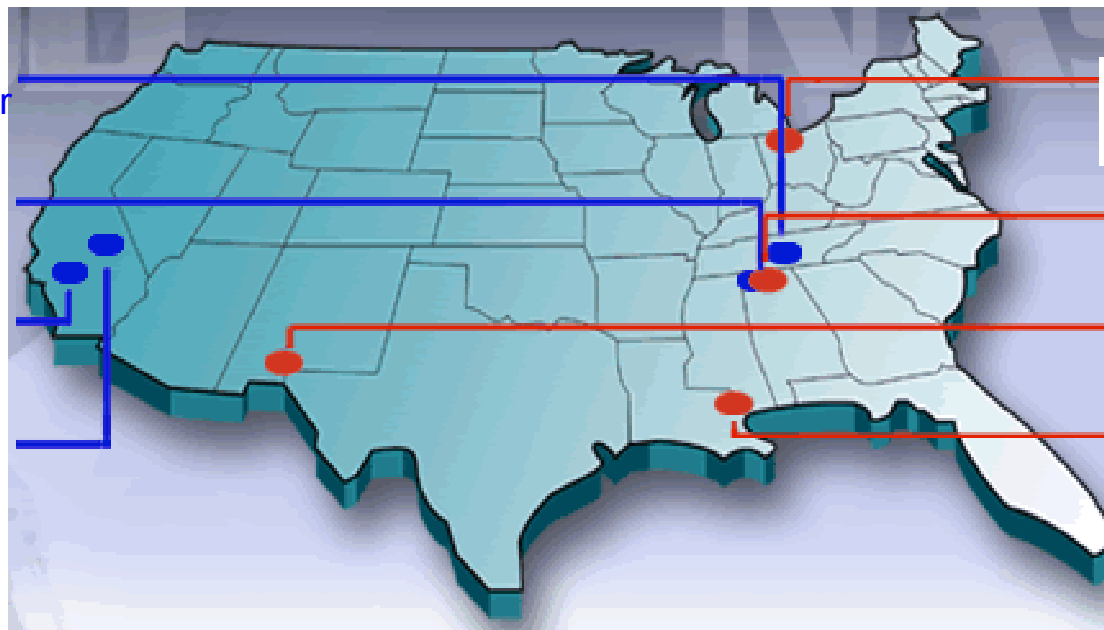
## DoD Sites

Arnold Engineering  
Development Center

Redstone Arsenal

Edwards AFB,  
AFRL

Naval Warfare,  
China Lake



## NASA Sites

Glenn Research Center  
Plum Brook Station

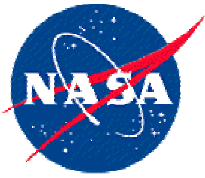
Marshall Space  
Flight Center

White Sands  
Test Facility

Stennis Space Center

<https://rockettest.ssc.nasa.gov>





# DOD LRE Test Capabilities

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*AIAA LRE Course*

- Significant World Class Assets for Liquid Rocket Propulsion
  - Air Force Research Lab (AFRL, a.k.a. “rocket lab”), in CA.
    - Sea-Level Stands 2-A (components), and 1-D (engines)
  - Arnold Engineering Development Center (AEDC), in TN.
    - Altitude Simulation Stand J-4 (engines)



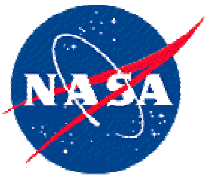


# Commercial LRE Test Capabilities

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*AIAA LRE Course*

- Pratt & Whitney at West Palm Beach, FL.
  - Test stands E-6 and E-8
  - Conducted testing of SSME advance turbopump, and upper stage engine
- Northrup Grumman (was TRW) at San Juan Capistrano, CA.
  - Several test stands
  - Conducted testing of Lunar Lander in 1960s
- Rocketdyne at Santa Susanna Field Lab in CA.
  - RS-27 engine test to be retired with fleet; future of stands TBD
- Aerojet at Sacramento, CA.
  - Several test stands
  - Titan core liquid propulsion to be retired with fleet; future is TBD
- Other commercial entities
  - SpaceX corp. in TX; currently testing the Falcon launcher LRE's



# University Test Capability

*AIAA LRE Course*

## Constellation University Institutes Program

- REAP = Rocket Engine Advancement Program
- Significant Test Capabilities
  - Penn State, Purdue, UAH, for liquid rocket engine technology
  - SOA for Plume Diagnostics, and Computational Modeling

### Rocket Engine Advancement Program Institute



Alabama-Huntsville



Purdue



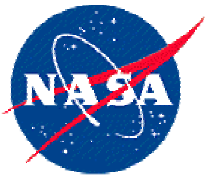
Penn State



Auburn



Tuskegee



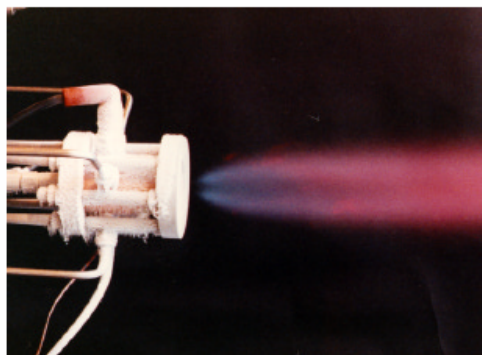
# Penn State University

*AIAA LRE Course*

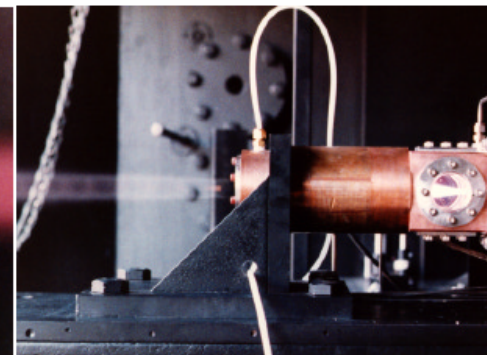
## PROPULSION ENGINEERING RESEARCH CENTER

POC: Prof. Bob Santoro and Dr. Sibtosch Pal  
(Dept. of Mechanical Engineering)  
- CRYOGENIC COMBUSTION LAB

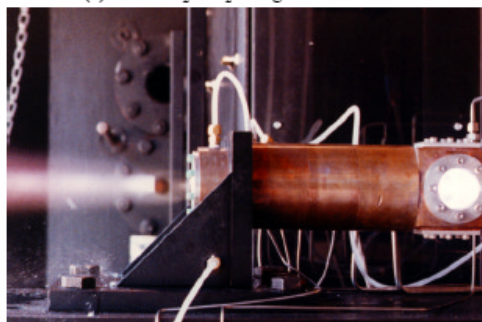
Representative LRE Injector Studies  
Performance & Mixing  
Combustion Stability  
Heat Transfer  
Non-Intrusive Diagnostics



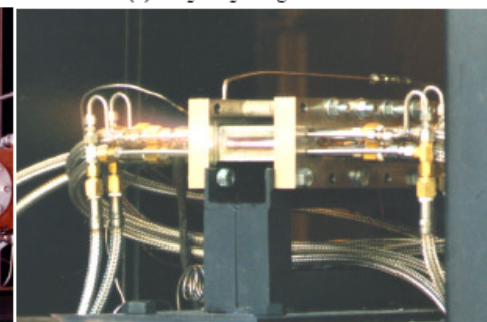
(a) First  $\text{LO}_2/\text{GH}_2$  firing at CCL.



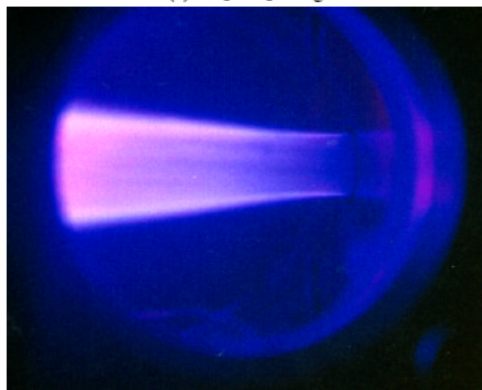
(b)  $\text{GO}_2/\text{GH}_2$  firing.



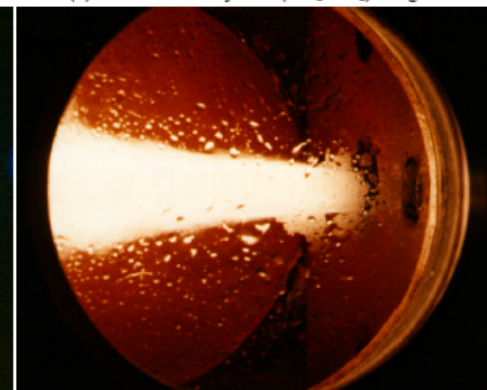
(c)  $\text{LO}_2/\text{GH}_2$  firing.



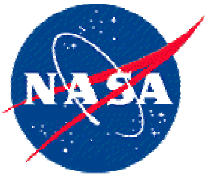
(d) RBCC rocket-ejector ( $\text{GO}_2/\text{GH}_2$ ) firing.



(e) UV closeup for  $\text{GO}_2/\text{RP-1}/\text{GH}_2$  firing..



(f) Injector closeup for  $\text{GO}_2/\text{RP-1}/\text{GH}_2$  firing.



# Penn State “PERC” (cont.)

AIAA LRE Course

## PROPULSION ENGINEERING RESEARCH CENTER

(cf. Santoro et al., AIAA Paper No.2001-0748)

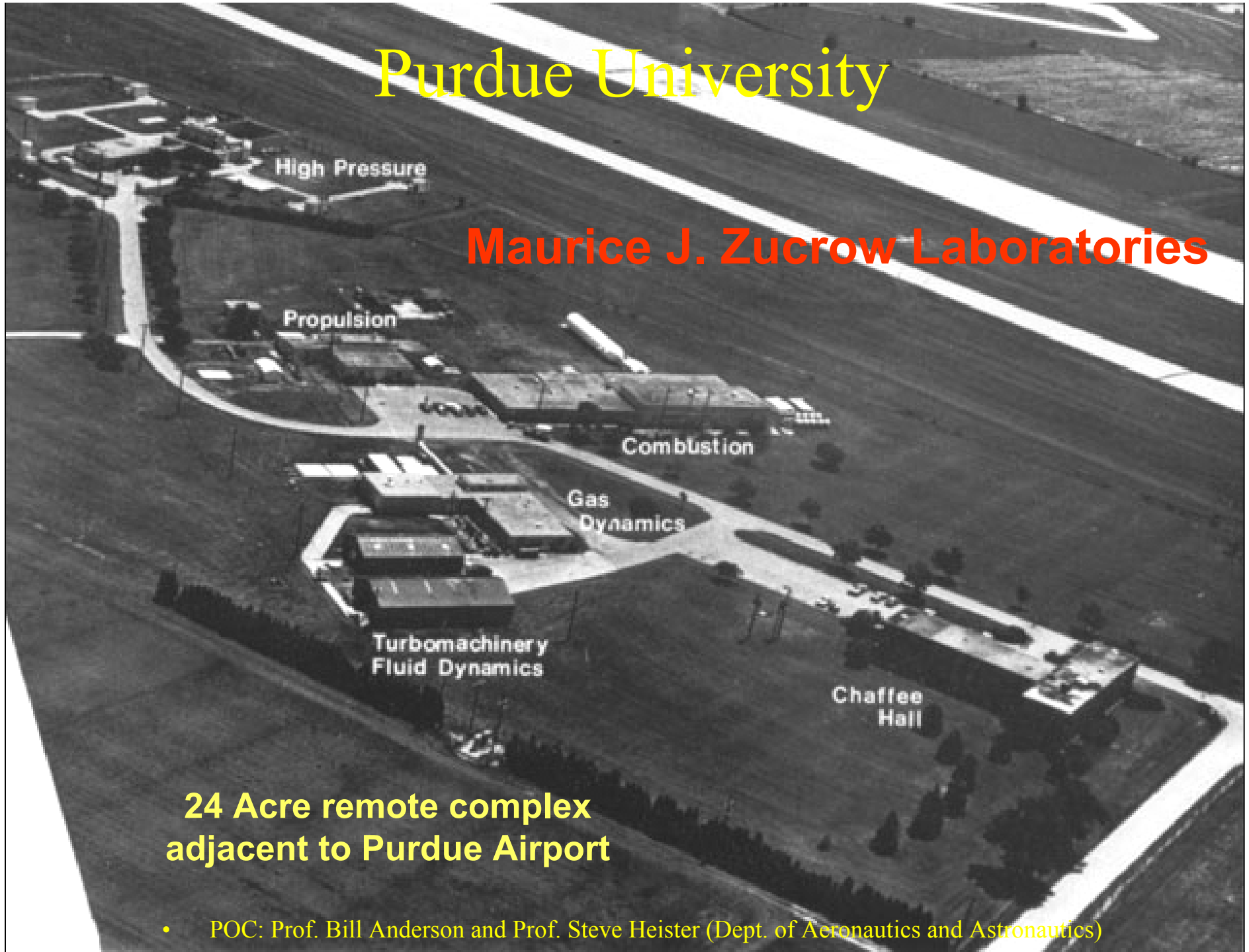
System	Diagnostic	Measurements
2 component PDPA system	drop size and velocity	<ul style="list-style-type: none"> <li>measuring LOX, methanol and RP-1 drops under hot-fire conditions.</li> </ul>
2-component LDV system	2 -component velocity	<ul style="list-style-type: none"> <li>characterizing velocity field for <math>\text{GO}_2/\text{GH}_2</math> combustor flowfield for shear coaxial element.</li> </ul>
Raman system (Nd:Yag laser/Flash pumped dye laser + ICCD camera)	species measurements	<ul style="list-style-type: none"> <li>measuring <math>\text{H}_2</math>, <math>\text{O}_2</math> and <math>\text{H}_2\text{O}</math> species for various injectors (<math>\text{GO}_2/\text{GH}_2</math> propellants) at pressures up to 1000 psia.</li> <li>measuring <math>\text{H}_2</math>, <math>\text{O}_2</math>, <math>\text{N}_2</math> and <math>\text{H}_2\text{O}</math> species in RBCC rocket-ejector environment</li> <li>marking combustion zone for shear layers.</li> </ul>
Planar Laser Induced Fluorescence System (Nd: Yag laser + Dye laser + frequency doubler + ICCD camera)	OH- radical measurements	
Laser Induced Incandescence	soot	<ul style="list-style-type: none"> <li>soot concentration measurements in hydrocarbon fuel flames at pressures up to 150 psia.</li> </ul>
High speed cinematography	dynamic event capture @ 8000 fps	<ul style="list-style-type: none"> <li>atomization and combustion phenomena.</li> </ul>
Schlieren photography	density gradient visualization	<ul style="list-style-type: none"> <li>reacting shear layer, two-phase flow injection, super-critical injection.</li> </ul>

# Purdue University

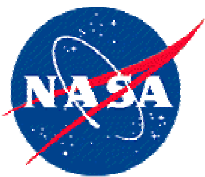
## Maurice J. Zucrow Laboratories

**24 Acre remote complex  
adjacent to Purdue Airport**

- POC: Prof. Bill Anderson and Prof. Steve Heister (Dept. of Aeronautics and Astronautics)







# Purdue “Zucrow Lab” (cont.)

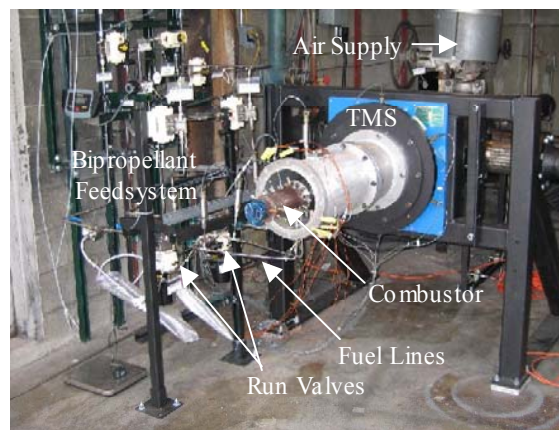
*AIAA LRE Course*



**Component Test & Validation**



**Test & Evaluation**



**Assembly & Installation**





# SUMMARY

*AIAA LRE Course*

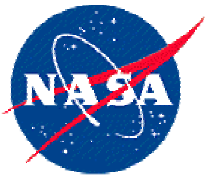
- Comprehensive Liquid Rocket Engine testing is essential to risk reduction for Space Flight
- Test capability represents significant national investments in expertise and infrastructure
- Historical experience underpins current test capabilities
- Test facilities continually seek alignment with national space development goals and objectives including government and commercial sectors

# Test What You Fly

B-2 Test Stand  
Stennis Space Center  
(Delta 4 Stage installation)

Ref: RS-68 Presentation  
(Rocketdyne web-site)

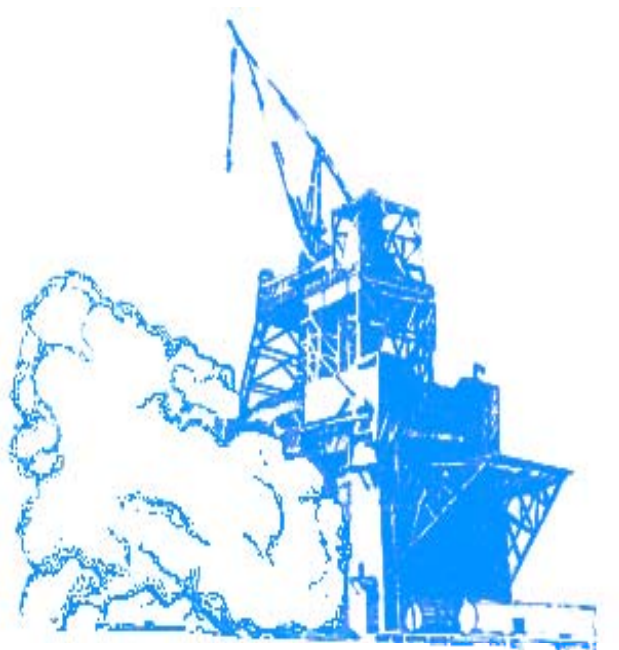




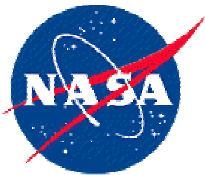
# BACKUP SLIDES

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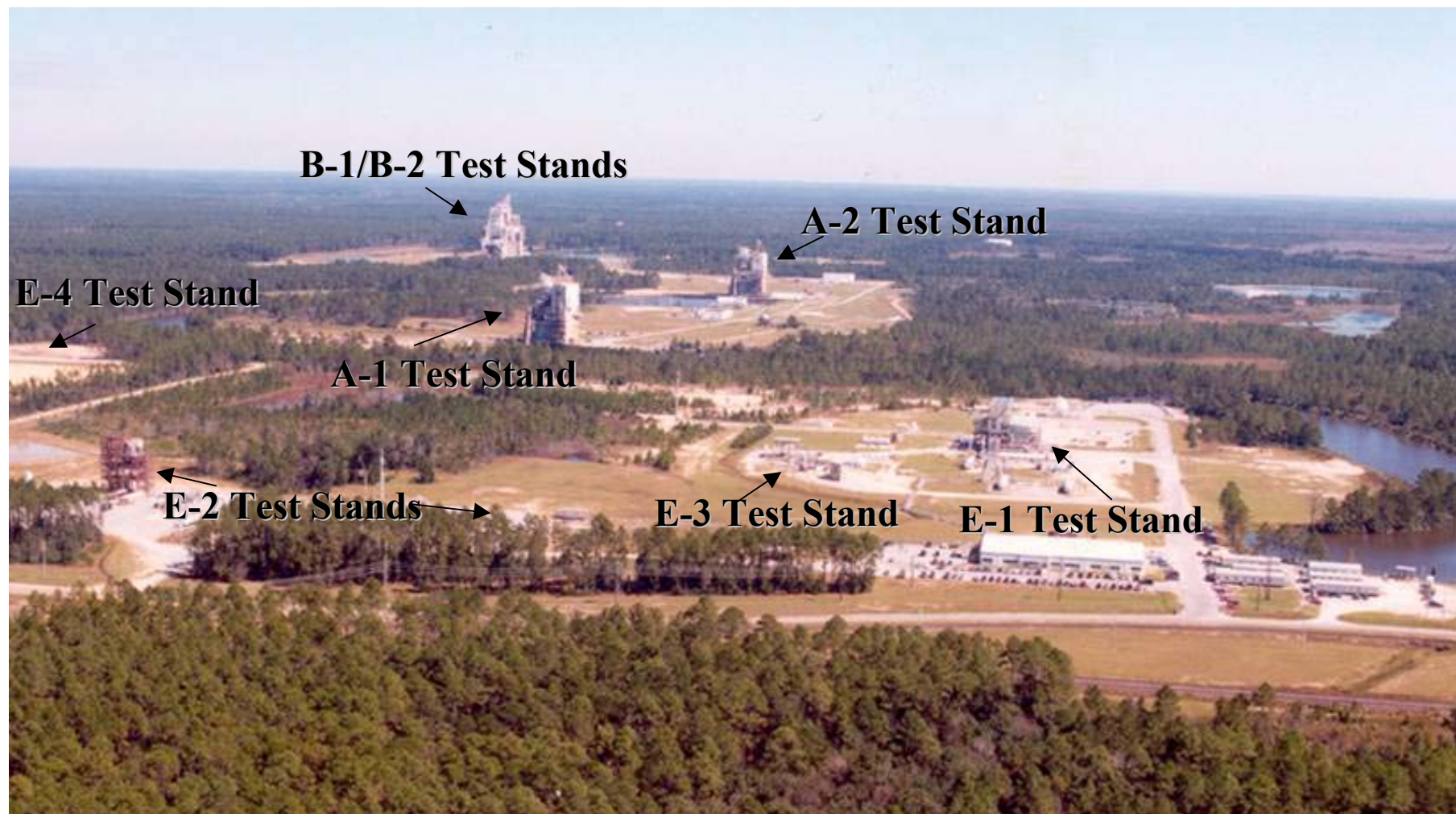


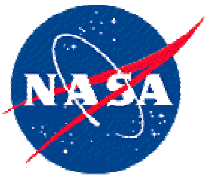




# SSC Test Stand Layout

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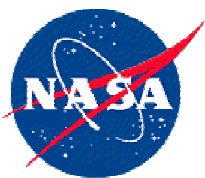
# E-Complex History

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- Late 1980s/Early 1990's
  - DoD/NASA Advanced Launch System and National Launch System
  - National Aerospace Plane
  
- Construction Starts
  - E-1 1989
  - E-2 1991
  - E-3 1995
  
- First Test
  - E-1 1999
  - E-2 1994
  - E-3 1995







# SSC E-1 Test Stand Projects

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**250 Klbf Hybrid ... 4 tests**  
(1999, 2001)



**TRW 650K TCA ... 15 tests**  
**Hot-Fire**  
(Summer 2000)



**240 Klbf Aerospike ... 17 tests**  
(1999-2001)



**RTF SSME Accep (8-19-04)**



**IPD (250K-scale) LOX Pump**  
**Cold-Flow**  
(Fall 2002)



**IPD Ox Rich Preb ... 9 tests**  
**Hot Fire**  
(Sep - Oct 2002)



**IPD Eng. Install (10-15-04)**



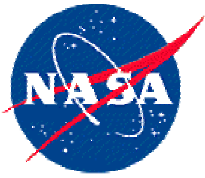
**Subscale Ox-Rich Preb ... 15 tests**  
(RS-76: Nov 98 – Jan 99)  
(RS-84: Fall 2003)



**IPD LOX Pump ... 12 tests**  
**Hot Fire**  
(Mar - May 2003)



**IPD LH Pump ... 6 tests**  
**Cold-Flow**  
(May - Nov 2004)

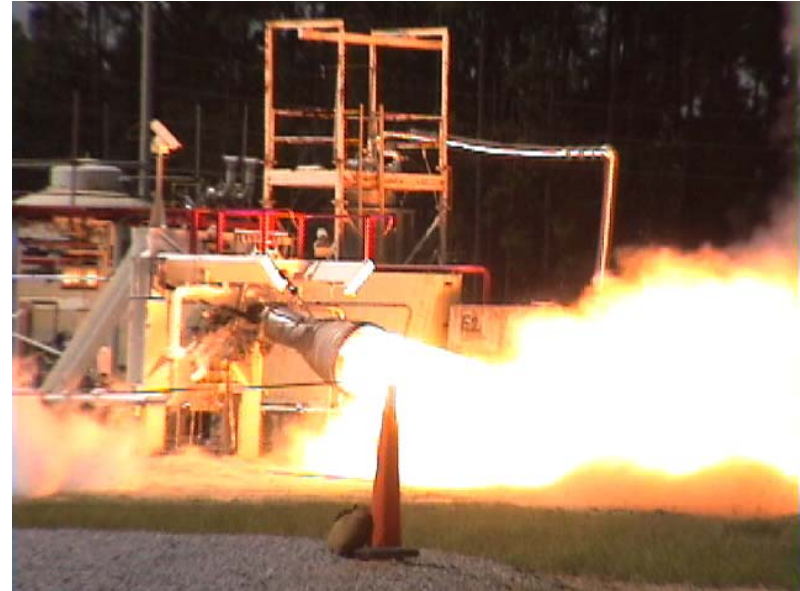


# SSC E-2 Test Stand

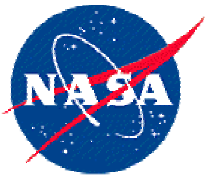
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E-2 Cell 1 Test of RS-84 LOX Rich Preburner



E-2 Cell 1 Test of LR-89 LOX/RP Thrust Chamber



# SSC E-3 Test Stand Capabilities

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- E3 Test Stand Capabilities

- Primarily Designed for Rocket Engine Component & Sub-Scale Engine Development
- Comprised of Two (2) Test Cells

- E3 Cell 1

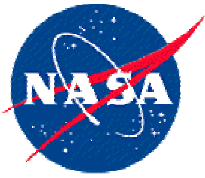
- Horizontal Test Cell
- Propellants:  $\text{LO}_2$ ,  $\text{GOX}$ , JP-8,  $\text{GH}_2$
- Support Gasses:  $\text{LN}_2$ ,  $\text{GN}_2$ ,  $\text{GHe}$
- Thrust Loads up to 60K  $\text{lb}_f$

- E3 Cell 2

- Vertical Test Cell
- Propellants:  $\text{LO}_2$ ,  $\text{H}_2\text{O}_2$ , JP-8
- Support Gasses:  $\text{LN}_2$ ,  $\text{GN}_2$ ,  $\text{GHe}$
- Thrust Loads up to 25K  $\text{lb}_f$







# SSC E-3 Test Stand Projects

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## Hydrogen Peroxide Programs (50% to 98%)



- Tested Several H<sub>2</sub>O<sub>2</sub> Test Articles
  - Boeing AR2-3
  - OSC Upper Stage Flight Experiment
  - Pratt & Whitney Catalyst Bed

